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TAU LEPTONS AND TOP QUARKS IN A 'NON-LOCAL' BARYOGENESIS AT THE ELECTROWEAK PHASE TRANSITION

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ABSTRACT [1]

Baryon asymmetry can be generated at the first order electroweak phase transition, provided there is a CP violation on the bubble wall. In this report we discuss the role of leptons and quarks in the 'non-local' baryogenesis mechanism.

It is quite a remarkable fact that baryogenesis may have occurred at the electroweak phase transition [1] with a minimal extension of the Higgs sector, in order to provide for the necessary CP violation [2].

CP violation in a two complex Higgs doublet model is secured by a CP-odd scalar field which changes in a definite manner on the bubble wall, as specified by the Higgs potential. This field couples through the anomaly, producing a bias in the baryon violating processes, and therefore the possibility of baryon production [3].

Cohen, Kaplan and Nelson [4] have proposed a non-local 'charge transport' mechanism: the *top* quark asymmetry generated by a CP-violating reflection off the wall propagates far into the unbroken phase, and biases the baryon production.

In comparison to a 'local' baryogenesis occurring on the wall, there are two main advantages to the 'nonlocal' baryogenesis:

[1]This lecture is based on a collaboration with Michael Joyce and Neil Turok. The lecture was delivered at the NATO Advanced Research Workshop on 'ELECTROWEAK PHYSICS AND THE EARLY UNIVERSE' held at Sintra, Portugal from March 22 to 25, 1994.

(a) the anomalous baryon number violating rate is unsupressed in the unbroken phase, while it becomes exponentially suppressed on the wall,

(b) the extent over which baryogenesis takes place is much larger, it is specified by the properties of the diffusion tail in front of the wall.

In this work we will focus on discussing the role of various particle species in a 'non-local' baryogenesis, in particular we will compare the roles of the *top* quark and τ-lepton. Before we proceed, we review the main steps involved in the calculation of the asymmetry.

In an analytic treatment, the problem of calculating the baryon number can be broken up into: (a) modeling the reflection off the wall, which sources (b) the diffusion equations, thus specifying the profiles of particle species in front of the wall; (c) the effects of the hypercharge screening on propagation of the asymmetry, and finally, (d) integration of the baryon rate equation.

(a) *Reflection.* Treatment of the reflection problem using the perturbative Dirac equation is valid only in the thin wall limit: $Lm \leq 1$, which for the *top* quark gives a bound: $L \leq 1/T$. Perturbative calculations suggest $L \approx 20 - 40/T$. For τ-leptons this bound is marginally satisfied. When the wall is much thicker than the mean free path of a particle, the reflected asymmetry is exponentially suppressed due to the loss of coherence [5]. In the thin wall limit the perturbative Dirac equation gives the reflected chiral particle asymmetry proportional to the mass squared, wall velocity (v_w), CP-violation in the wall ($\Delta\theta_{CP}$), and inversely proportional to the thickness of the wall (m_H):

$$J_L(0) = -J_R(0) \approx \frac{v_w m^2 m_H \Delta\theta_{CP}}{4\pi^2} \tag{1}$$

Note that this is a purely chiral current, which, after it thermalizes, diffuses in front of the wall. To calculate the distribution of the diffusing particles, we model the source to the diffusion equations by the chiral current in eq. (1).

(c) *Diffusion.* Propagation of the asymmetry in front of the wall is specified by the diffusion equations or particle densities n_i in the rest frame of the wall ($x = z - v_w t$)

$$D_i n_i'' + v_W n_i' \Sigma_A \Gamma_A \Sigma_j \mu_j = J_i'(x) \tag{2}$$

where v_w denotes the velocity of the wall, D_i diffusion constant of the particle species i, Γ_A is the rate for a process A, and $\Sigma_j \mu_j$ is the sum of the chemical potentials on the external legs of the process A. The extension of the source ξ_i is defined as $\xi_i J_i^0 = \int J_i$.

(d) *Baryon rate equation.* The rate of baryon production in the unbroken phase is determined by the following rate equation:

$$\dot{B} = -\frac{N_f \Gamma_s}{T} \Sigma_i \mu_i, \tag{3}$$

where $\Gamma_s = \kappa \alpha_w^4 T$ is the weak sphaleron rate ($\kappa \in [0.1, 1]$), $N_f = 6$ is the number of the fermionic flavors, and $\Sigma_i \mu_i$ is the sum over the chemical potentials for the left-handed particles.

Now we are ready to discuss the role of leptons and quarks in the 'non-local' baryogenesis. Because of their much larger tree-level mass, *top* quarks and τ-leptons are reflected much more abundantly, and therefore require no further consideration.

Let us first discuss the propagation of leptons. The relevant diffusion equations for the third family chiral leptons (L_L and L_R) in the wall rest frame are static:

$$D_L L_L'' + v_w L_L' - \Gamma_{LR}(aL_L - bL_R) = J_L' \tag{4}$$
$$D_R L_R'' + v_w L_R' + \Gamma_{LR}(aL_L - bL_R) = J_R' \tag{5}$$

In the above we also include the dominant decay channel, which converts the left-handed leptons into the right-handed ones *via* emission of a Higgs. For leptons: $\Gamma_{LR} \approx 0.3\alpha_w y_\tau^2 T$, where y_τ is the τ-lepton Yukawa coupling constant, α_w the $SU(2)$ coupling constant, $a \approx 1/2$, $b \approx 1$. (Here we assume that the Higgs particles do not significantly affect the lepton distribution function, as it was argued in[6].)

From eq. (3), we infer that the relevant quantity to calculate, which is proportional to the baryon number, is the integral of the left-handed lepton number in front of the wall, which can be obtained in quite a simple manner. After summing and integrating twice eqs. (5) we get

$$\int_0^{+\infty} L_L = \frac{b}{a+b}\frac{\int_{-\infty}^{+\infty}(J_L + J_R)}{v_w} \tag{6}$$

To obtain this expression we used the fact that the dominant contribution to the lepton integral comes from the diffusion tail in front of the wall, in which $aL_L = bL_R$, and also that any lepton number vanish at the spatial infinity. The above integral gives the correct result for the integrated lepton number for slow walls, for which the diffusion tail extends far into the unbroken phase: $v_w^2 << \Gamma_{LR} D_R < 1$.

Next we discuss the *top* quark case. We can write the analogous equations for the left- and right-handed baryons (B_L and B_R), with the decay term changed to $\Gamma_{ss}(B_L - B_R)$, where Γ_{ss} is the strong sphaleron rate. Nevertheless, the simple trick applied in solving the lepton equations does not work, because the diffusion constants for left and right handed quarks are roughly the same. This has as a consequence: $J_{B_L} \approx -J_{B_R}$, so that $B = B_L + B_R$ is not directly sourced by any current, and there is no diffusion tail for baryons in front of the wall. The main source for the baryon number comes from the strong sphaleron tail $(D_q/2\Gamma_{ss})^{1/2}$ for $B_L - B_R$. The result is

$$\int_0^{\infty}(B_L - B_R) = \frac{1}{4}\frac{\int(J_{B_L} - J_{B_R})}{\sqrt{2\Gamma_{ss}D_q}} \tag{7}$$

The ratio of the baryon numbers for the *top* quark and the τ-lepton cases then reads:

$$\frac{B_{top}}{B_\tau} = \frac{1}{4}\frac{a+b}{b}\frac{v_w}{\sqrt{2\Gamma_{ss}D_q}}\frac{\int(J_{B_L} - J_{B_R})}{\int(J_{L_L} - J_{L_R})} \approx \frac{3}{8}\frac{v_w}{\sqrt{2\Gamma_{ss}D_q}}\frac{D_q}{D_{\tau_R}}\left(\frac{m_t(T)}{m_\tau(T)}\right)^2 \tag{8}$$

There are two reasons for the *top* quark suppression. *Firstly*, there is no diffusion tail for *top*s; the strong sphalerons cut it off in front of the wall, giving a suppression factor of approximately 10. *Secondly,* the extent of the source current (before it thermalizes) is larger for the right handed τ-leptons at least by the ratio of the diffusion constants $D_{\tau_R}/D_q \sim 50$. In the case of thicker walls, this suppression tends to be stronger than linear, because the *top*s have the tendency to be thermalized before they escape the region of the wall, and thus be lost as a source for the diffusion equations.

Naively, these two sources of suppression might be outweighed by the large ratio of *top*-to-τ mass: in the standard model $m_t^2/m_\tau^2 \sim 10^4$, such that the *top* still contributes

more to the asymmetry than the τ. However, in the two Higgs doublet theory, quarks and leptons may couple to the different Higgs, which may have different zero temperature *vev*s, giving the possibility that around the phase transition the *top*-to-τ mass ratio be much larger than at the zero temperature. In this case the τ-lepton produces more baryons.

And as a concluding remark, we announce the result of the recent work [6] on thicker walls (comparable to the perturbative result: $20 - 40/T$). We consider the case when the wall thickness is much larger than the mean free path of particles, which justifies the usage of the fluid equations approximation, but still thinner than the relevant diffusion length D/v_w. We find that, besides the reflection, there is a *classical force* due to the CP-violation on the bubble wall acting differentially on particle species, causing a diffusion tail in an axial particle number in front of the wall. We find that the effect is proportional to the mass squared of the particles in consideration and *independent* on the diffusion properties of the species, singling out the *top* quark as the main candidate for baryogenesis!

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References

[1] V. Kuzmin, V. Rubakov and M. Shaposhnikov, Phys. Lett. **155B**, 36 (1985); F. Klinkhamer and N. Manton, Phys. Rev. **D30**, 2212 (1984).

[2] N. Turok and J. Zadrozny, Phys. Rev. Lett. **65**, 2331 (1990); N. Turok and J. Zadrozny, Nuc. Phys. **B 358**, 471 (1991); L. McLerran, M. Shaposhnikov, N. Turok and M. Voloshin, Phys. Lett. **256B**, 451 (1991).

[3] N. Turok, in *Perspectives in Higgs Physics*, *ed.* by G. Kane, pub. World Scientific, p. 300 (1992); A. Cohen, D. Kaplan and A. Nelson, Ann. Rev. Nucl. Part. Phys. **43** 27-70 (1993).

[4] A. Cohen, D. Kaplan and A. Nelson, Nuc. Phys. **B373**, 453 (1992); A. Cohen, D. Kaplan and A. Nelson, Phys. Lett. **B294** (1992) 57.

[5] M. B. Gavela, P. Hernández, J. Orloff, and O. Pène, *Standard Model CP-violation and Baryon Asymmetry*, preprint CERN 93/7081, LPTHE Orsay-93/48, HUTP-93/A036, HD-THEP-93-45 (1993); Patrick Huet and Eric Sather, *Electroweak Baryogenesis and Standard Model CP-violation*, SLAC-PUB-6479, April, 1994.

[6] Michael Joyce, Tomislav Prokopec, and Neil Turok, *Classical Baryogenesis at the Electroweak Phase Transition*, PUPT preprint (1994).